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Evaluating exposure from electric fields in a high voltage switchyard according to the EU directive

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Abstract

An assessment according to Directive 2013/35/EU of exposure in a 400 kV switchyard has been performed. Part of the body was exposed to electric field strength above the high action level. We therefore performed simulations of the electric fields induced in the body to assess these accoding to the exposure limit values (ELVs). The simulations show that as long as the body is not grounded nor touching any grounded metallic objects, worker exposure is compliant with the directive. When grounded metallic objects are touched with hand or foot the ELV are exceeded. The ELV is exceeded already at very low contact currents (2–3 μA) in the finger. If not appropriate measures are taken, this would lead to a severe limitation of the work tasks that can be performed in switchyards.

Keywords: electric field, worker exposure, simulation, contact current, EU directive

(Some figures may appear in colour only in the online journal)

1. Introduction

The Directive 2013/35/EU on minimum health and safety requirements regarding the exposure of workers to the risks arising from electromagnetic fields is mandatory within the

European Union from 1 July 2016. The exposure limit values (ELVs) in the frequency range 1 Hz to 10 MHz are given in terms of the electric field strength induced in the body. The electric field strength induced cannot be measured, but only calculated by numerical simulations. In order to simplify the assessment of exposure, action levels (ALs) are given. The action levels are expressed as electric and magnetic fields to which an individual may be exposed without any adverse effects and with acceptable safety factors, i.e. that ELVs would not be exceeded. AL for contact current is given in order to limit indirect effects.

Most workplaces are expected to comply with the action levels in the Directive. In work places that use high currents or voltages action levels may be exceeded and further action would be required. If field levels cannot be easily reduced, an assessment against ELVs has to be performed. One area where this is the case, involves work in high voltage switchyards (Deschamps *et al* 2011).

A real case where work is performed in a 400 kV switchyard has been studied. If an individual, working in an electric field, would be touching a grounded object, the ELV can easily be exceeded. The contact current is less than a tenth of the AL for contact current.

Similar observations of exceeding the ELV for small contact currents have been made for skin to metal contact (Chan *et al* 2015). Several researchers have made simulations of the electric field strength induced in the body during magnetic field exposure, for a review see Magne and Deschamps (2016).

Simulations of electric field exposure are quite complicated and only a few cases have been published, e.g. Dimbylow 2005, Findlay 2013, Stuchly and Dawson 2000, Tarao *et al* 2013 and Tarao *et al* 2016.

2. Materials and methods

In order to calculate the electric field induced in the body the International Commission on Non-Ionising Radiation Protection (ICNIRP) (2010) recommends that the field be averaged over a $2 \times 2 \times 2$ mm volume of contiguous tissue. Thus, the resolution has to be higher than 2 mm for the averaging to have any significance. The number of cells, or voxels, required to resolve an average human body with 1 mm resolution is approximately $1760 \times 600 \times 300 = 317$ million cells, more cells than what can be handled for electric field simulations on our 64 Gb RAM computer. For whole body models, a resolution of 2 mm had to be used.

A significant difference between simulating the induced fields from electric field sources and magnetic field sources is that a much larger volume has to be included in electrical field source simulations. For magnetic fields, it is usually sufficient to model only the target body with high resolution as surroundings and sources do not have to be included in the computational domain.

In the case of electric field sources, the computational volume has to include not only the target and source but also all conducting objects, ground plane and free space to ensure that the boundaries of the model do not influence the electric field strength at the target.

One application where this quickly becomes a problem is the assessment of exposure to electric fields for workers in high voltage switchyards and near high voltage power lines.

Due to the large size of sources, often tens of meters, the computational volume and number of cells become very large—several billions.

To reduce the problem of large computation space a two-step simulation, similar to the method used in Stuchly and Dawson (2000) is used. In the first step, the potential distribution around the target is calculated using a relatively coarse grid. In the second step, a cage consisting of rectangular plates is built around the target (figure 1).

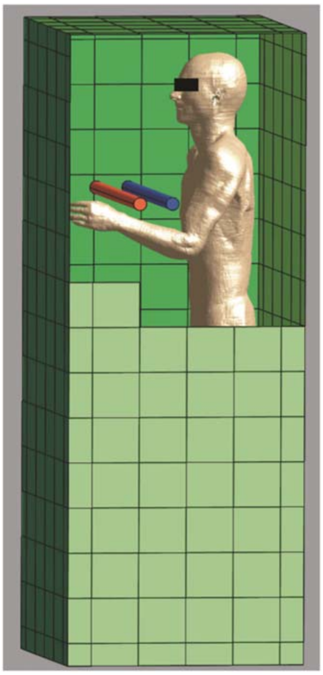

Figure 1. Shows a cage consisting of rectangular plates built around the body that is used in the second step of the simulation. The potentials calculated in the first step are applied on each plate.

The potential of the plates is set to the values obtained in Step 1. The volume outside the cage needs no longer be part of the simulation and a 2 mm resolution can be used for simulating the electric field inside the target body.

The size of the plates and distance between plates and human model will influence the simulated values. In our simulation, the plates are approximately 0.15×0.15 m and placed side-by-side. The distance between the human model and the plates is 90 mm to the back, 150 mm to the sides; the minimum distance is 50 mm.

Tarao *et al* (2013) used the two-step simulation for the Duke model in an electric field with a slightly narrower cage than in our simulation. They validated the simulation method by comparing it with an analytical solution, assuming a prolate semi-spheroid model of a biological substance. The average electric field inside the spheroid obtained by the numerical calculation and the analytical value agreed within less than 2%. However, the excellent agreement of the average field does not imply the same accuracy in every single voxel.

The external electric field and the induced electric field in the body have been simulated using the Sim4Life V2.2, ZMT Zurich MedTech software (Zurich, Switzerland). This software can be used to simulate the exposure from both electric and magnetic fields. Highly detailed whole body virtual human models developed by IT'IS Foundation (Christ *et al* 2010, Gosselin *et al* 2014) have been used. In the simulation described, the Duke cV3.1 human phantom is used as a target.

Electrical properties of the body organs are given in the IT'IS database v2.7 in combination with the IT'IS low frequency database V3.0. Notably the conductivity of the skin is

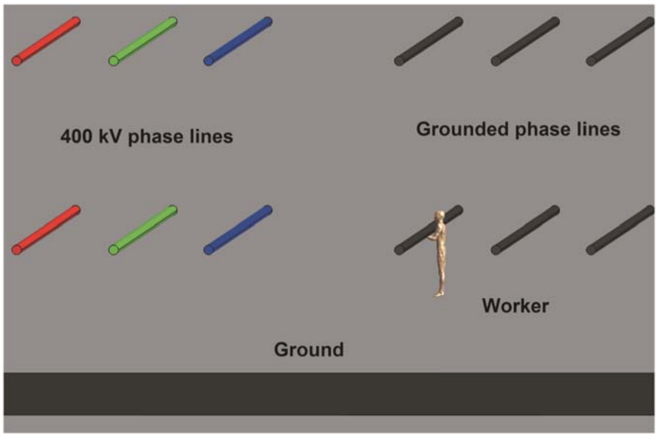

Figure 2. Worker close to grounded phase lines with live 400 kV phase lines in adjacent bay. Note that the figure is not drawn to scale.

chosen as 'wet skin' 0.1 s m^{-1}, which can be considered to be a realistic case, Dimbylow (2005), De Santis *et al* (2015). The electrical properties of the organs are given as isotropic values; in real some high water content tissues tend to be very anisotropic. Our model does not allow for anisotropy. An estimate of the uncertainty due to this might be achieved from Lee *et al* (2012) who simulated the electric field induced by electro-convulsive therapy in a realistic finite element head model where the conductivity of the brain white matter was modeled with and without anisotropy. The E-field magnitude relative error over the whole brain of the isotropic model compared to the anisotropic model was 6%–18%, depending on the type of stimulation electrodes.

A particular difficulty in this type of simulation is the huge difference in electric field strength in the body and adjacent air voxels. The simulations were performed using the Sim4Life convergence criteria of 10^{-11} or better for the relative solver tolerance.

2.1. Simulation cases

The background of the simulations is a real case where a worker is standing on a grounded base slab in a 400 kV substation bay, which is disconnected and grounded. This bay is to be disassembled while the adjacent bay is live at 400 kV (figure 2).

The undisturbed electric field without the worker is shown in figure 3. The field strength increases close to the grounded conductors; at a distance of 5 mm, the field strength is 70 kV m^{-1}.

The action level in the EU Directive refers to the undisturbed field. At 50 Hz, the low AL is 10 kV m^{-1} and the high AL is 20 kV m^{-1}. As seen in figure 3, the worker is partially exposed to fields above the ALs. The 2013 Directive states, 'the ALs represent maximum calculated or measured values at the workers' body position. This results in a conservative exposure assessment and automatic compliance with ELVs'. In our case, the maximum exposure exceeds the ALs, thus an assessment against the ELVs is needed.

Simulations of the electric field induced in the body of the worker, standing on the base slab, for five cases have been performed:

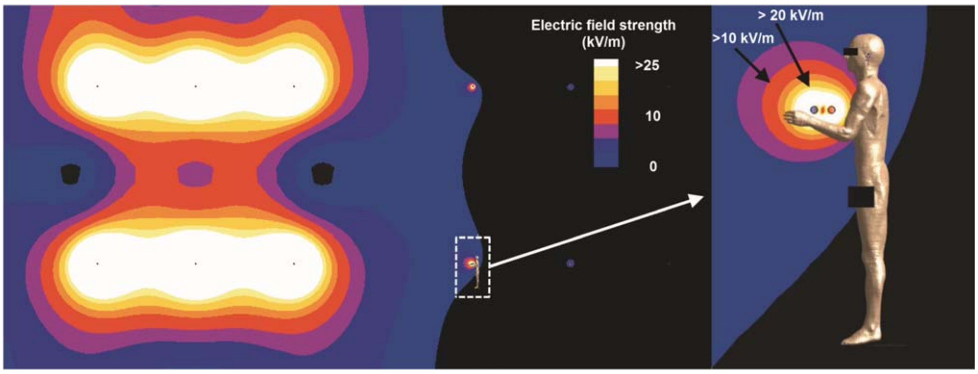

Figure 3. Shows undisturbed electric field strengths with a live bay and a grounded bay. Enlarged picture of the worker is shown to the right. The worker is shown for reference only and was not present in the simulation.

Case 1: Standing on a non-conducting slab without touching the conductors

Case 2: Standing with insulating shoes, with a sole of 5 mm thickness, on a grounded metal slab without touching the conductors

Case 3: Standing barefoot, with a total contact area of approximately10 cm^2, on a grounded metal slab without touching the conductors

Case 4: Standing with insulating shoes, with a sole of 5 mm thickness, on a grounded metal slab touching a conductor with one bare finger, with a contact area of approximately 0.6 cm^2

Case 5: Standing with insulating shoes, with a sole of 5 mm thickness, on a grounded metal slab touching a conductor with one gloved finger

The insulating material for gloves and shoes has zero conductivity as this represents an extreme case.

For the first three cases, the worker position is shown in figure 3 and for case four and five in figure 4. The dimensions of the base slab are 1.6 × 1.6 m.

For the different cases the electric field strength induced is simulated in the body, as well as the induced current density in the central nervous system (CNS). In the cases where skin is in direct contact with metallic objects, the contact current is calculated.

3. Results

The exposure is assessed according to Directive 2013/35/EU article 4.5 comprising ELVs and indirect effects. The electric field strength induced in the body, for the five cases of the worker standing on the base slab, has been summarised in table 1. Values are given for the single 2 mm voxel that had the highest value and for the 99th percentile. For Case 3, where there is a current via the foot, we also made a simulation with 1 mm resolution in the foot and 4 mm resolution in the rest of the body. For Case 4, where there is a contact current in the finger, we also made simulation with 0.5 mm resolution in the hand and 5 mm resolution in

Figure 4. Shows position of the worker when touching a conductor.

the rest of the body. For these two cases, we calculated the $2 \times 2 \times 2$ mm average electric field strength, as suggested by ICNIRP (2010).

The values shall be assessed against the ELVs. At 50 Hz the ELV for health effects is $0.8\ \mathrm{V\ m^{-1}}$ RMS and the ELV for sensory effects is $0.1\ \mathrm{V\ m^{-1}}$. The ELV for health effects covers all peripheral and CNS tissues whereas the ELV for sensory effects is restricted to the CNS in the head alone.

For all cases, the calculated fields in the brain are below the ELV for sensory effects. The ELV for health effects is exceeded for Cases 3 and 4 with skin to metal contact. The 99th percentile is still below the ELV, but this is not relevant for these cases, as the high values are limited to a small part of the body (finger or part of foot).

In the simulation, we were not able to follow the ICNIRP (2010) recommendation to use a $2 \times 2 \times 2$ mm average for the electrical field induced in the whole body, since the voxel size was 2 mm. Except where otherwise noted, the values in table 1 are not averaged but represent the highest for the specific tissue, which could lead to an overestimation due to stair-casing effects. To investigate this finding we made additional simulations with a higher resolution in the body part where the highest voxel value was found. In these cases, the averaged values were larger than the single $2 \times 2 \times 2$ mm voxel value. At least for these cases, stair-casing does not seem to be a major problem. ICNIRP (2010) also states 'For a specific tissue, the 99th percentile value of the electric field is the relevant value to be compared with the basic restriction'. The 99th percentile means that the 1% voxels with the highest values are dismissed. This might work well for tissues with a small spread but

Table 1. Induced electric field strength in the body of the worker, maximum and 99th percentile values.

	Case 1		Case 2		Case 3		Case 4		Case 5	
	Standing on a non-conducting slab without touching the conductors		Standing with insulating shoes on a grounded metal slab without touching the conductors		Standing barefoot on a grounded metal slab without touching the conductors		Standing with insulating shoes on a grounded metal slab touching a conductor with one bare finger		Standing with insulating shoes on a grounded metal slab touching a conductor with one gloved finger	
Electric field strength RMS	Max ($V\ m^{-1}$)	99th ($V\ m^{-1}$)	Max ($V\ m^{-1}$)	99th ($V\ m^{-1}$)	Max ($V\ m^{-1}$)	99th ($V\ m^{-1}$)	Max ($V\ m^{-1}$)	99th ($V\ m^{-1}$)	Max ($V\ m^{-1}$)	99th ($V\ m^{-1}$)
Skin	0.059	0.014	0.031[c]	0.016[c]	2.3/2.6[a]	0.017	22/27[b]	0.160	0.13	0.020
Brain	0.004	0.002	0.010	0.004	0.015	0.005	0.016	0.0060	0.011	0.0042

[a] Simulated with 1 mm resolution in the foot, average over $2 \times 2 \times 2$ mm.
[b] Simulated with 0.5 mm resolution in the hand, average over $2 \times 2 \times 2$ mm.
[c] The highest field strength was found in fat tissue, 0.048 $V\ m^{-1}$ maximum and 0.018 $V\ m^{-1}$ 99th percentile.

definitely not for tissues such as skin as illustrated by our Cases 3 and 4 where the limited number of skin voxels with high induced field strength is concentrated to the vicinity of the metal contact area. By applying the 99th percentile, all of these voxels are excluded, explaining why the averaged value is more than 100 times higher than the 99th percentile value. The underestimation of the field strength by using the 99th percentile has been reported by several authors; Bakker *et al* (2012), Laakso and Hirata (2012), Chen *et al* (2013), De Santis and Chen 2014 and Schmid *et al* (2013).

We have also calculated the induced current density, averaged over 1 cm^2, in the central nervous system tissues in the head and trunk, according to the former Directive 2004/40/EC 2004 which is based on ICNIRP (1998a) and ICNIRP (1998b) (see table 2). For the cases with skin to metal contact the contact current has been calculated.

The limit for workers (10 mA m^{-2}) in Directive 2004/40/EC 2004 has been fulfilled for all cases. The simulated contact current is below AL (1 mA in both Directive 2004/40/EC 2004 and Directive 2013/35/EU 2013). The field strength induced in the skin, in Case 4, is 34 times the ELV for health effects. In Case 3, the ELV is exceeded 3.2 times.

4. Discussion

The simulations in our scenario in the 400 kV switchyard show that as long as the body is not grounded and not touching any grounded metallic objects, the worker exposure is compliant with the Directive 2013/35/EU (2013) although parts of the body are above the action levels in Cases 1 and 2. When touching grounded metallic objects by hand or foot directly, the ELV is exceeded Cases 3 and 4. Case 5 shows that it is possible to touch metallic objects if insulating gloves and shoes are used. The insulation must be secured for all work conditions such as rain and perspiration. If any other body parts come in contact with grounded objects, they must also be insulated in a similar way.

As soon as there is a direct metal contact with body by either foot or hand (Cases 3 and 4), the exposure is well above the ELV for health effects but still below the ELV for sensory effects due to the fact that the ELV for sensory effects is restricted to the head.

A common assumption is that the limits in Directive 2013/35/EU are equally or less stringent than in the repealed Directive 2004/40/EC 2004 which is based on ICNIRP (1998a) where the ELVs have been expressed in current densities in the central nervous system. In Cases 3 and 4 we exceed the ELV in Directive 2013/35/EU but all our simulated cases are compliant with the corresponding limit in Directive 2004/40/EC 2004, as shown in table 1.

The ICNIRP (2010) states that the motive for contact current AL is to avoid shock and burn hazards but this is not clearly described in the Directive 2013/35/EU. The ICNIRP also states, ‘It should be noted that the reference levels are not intended to prevent perception but to avoid painful shocks. Perception of contact current is not *per se* hazardous but could be considered as annoyance.’

Chan *et al* (2015) calculated the electric field strength in a finger, with a contact current of 500 μA, of a child, to 169 V m^{-1} at 10 Hz and 157 V m^{-1} at 100 Hz. We have performed calculations on an adult and found similar results. As the health effect ELV is 0.8 V m^{-1} a contact current in the finger will be restricted to 2–3 μA. Directive 2004/40/EC 2004 was based on current density in CNS which allows for contact currents in the range of the AL. The current Directive 2013/35/EU is based on the electric field strength in CNS and peripheral nerves, which in practice allows contact current of only a few μA.

Table 2. Contact current and induced current density in the central nervous system of the worker

	Case 1		Case 2		Case 3		Case 4		Case 5	
	Standing on a non-conducting slab without touching the conductors		Standing with insulating shoes on a grounded metal slab without touching the conductors		Standing barefoot on a grounded metal slab without touching the conductors		Standing with insulating shoes on a grounded metal slab touching a conductor with one bare finger		Standing with insulating shoes on a grounded metal slab touching a conductor with one gloved finger	
Current density ICNIRP 1998 avg RMS	Max mA m^{-2}	99th mA m^{-2}	Max mA m^{-2}	99th mA m^{-2}	Max mA m^{-2}	99th mA m^{-2}	Max mA m^{-2}	99th mA m^{-2}	Max mA m^{-2}	99th mA m^{-2}
Spinal cord and lumbar plexus	3.0	2.6	3.2	2.8	6.8	5.7	5.2	4.7	4.0	3.4
Contact current					0.057 mA at ankle		0.068 mA at finger			

The contact current AL of 1 mA is set to prevent painful shocks, but you are not allowed to expose a worker to a contact current of 1 mA, as the health ELV is exceeded hundreds of times.

As the ICNIRP states that perception is not hazardous *per se*, one might question whether perception should be the basis for health effect ELV in peripheral nerves.

There are certain uncertainties in simulations of the electric field strength in the body; the used model is not of the actual worker, the conductivities of the tissues are not fully known and anisotropy of tissue conductivity is not considered. The computer limits the number of voxels and the two-step simulation introduces additional uncertainties. However, these uncertainties are not of the magnitude to falsify our main conclusion that a contact current of 1 mA can exceed the health ELV.

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